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Deilami et al.

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(54) **SYSTEMS AND METHODS FOR COMPENSATING A REDUCTANT DELIVERY SYSTEM IN AN AFTERTREATMENT SYSTEM OF AN INTERNAL COMBUSTION ENGINE**

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B01D 53/94	(2006.01)

(52) **U.S. Cl.**
CPC ***F01N 3/208*** (2013.01); ***B01D 53/9431*** (2013.01); ***B01D 53/9495*** (2013.01); *F01N 2900/1808* (2013.01); *F01N 2900/1812* (2013.01); *F01N 2900/1821* (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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423/213.2

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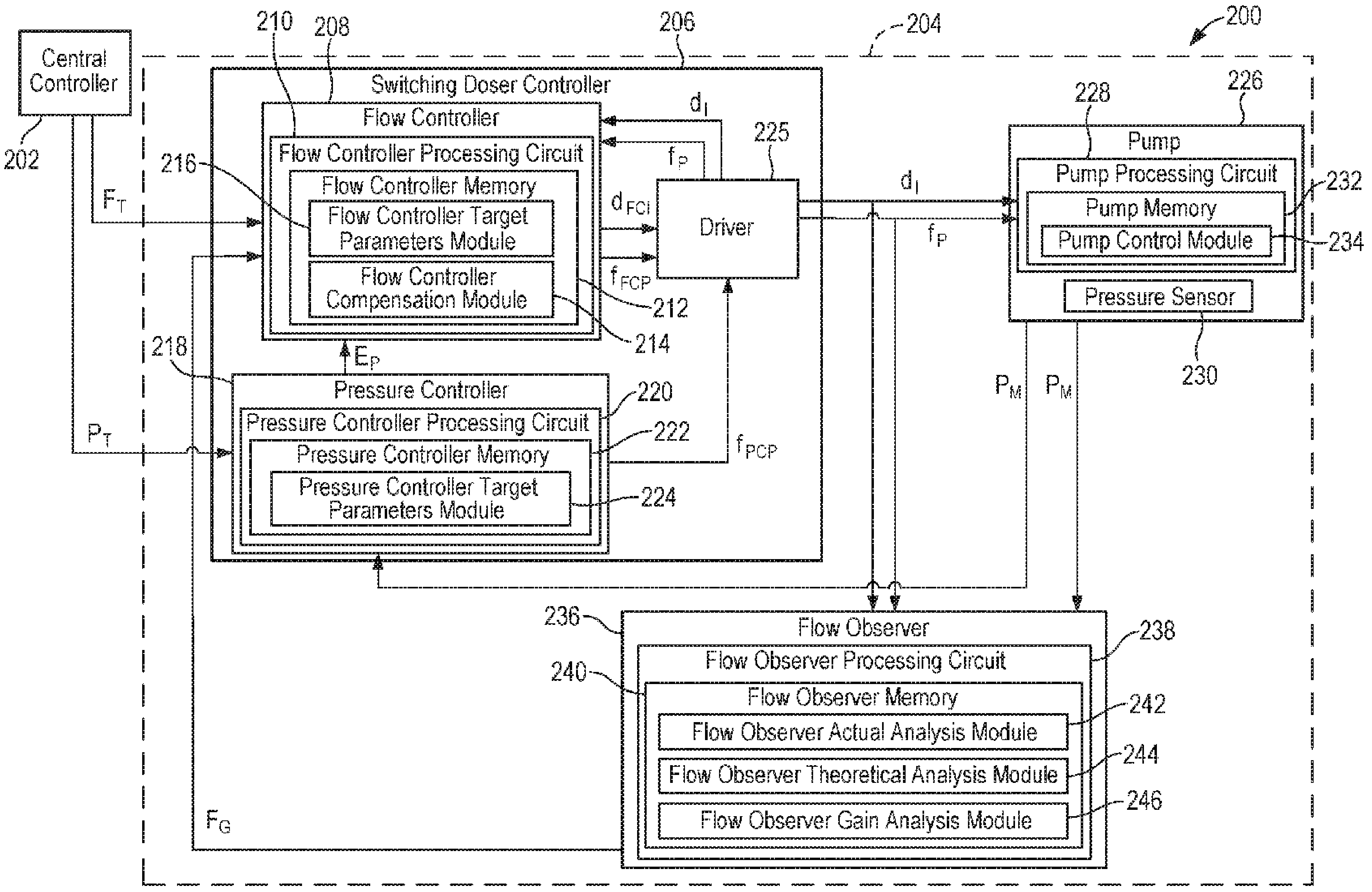
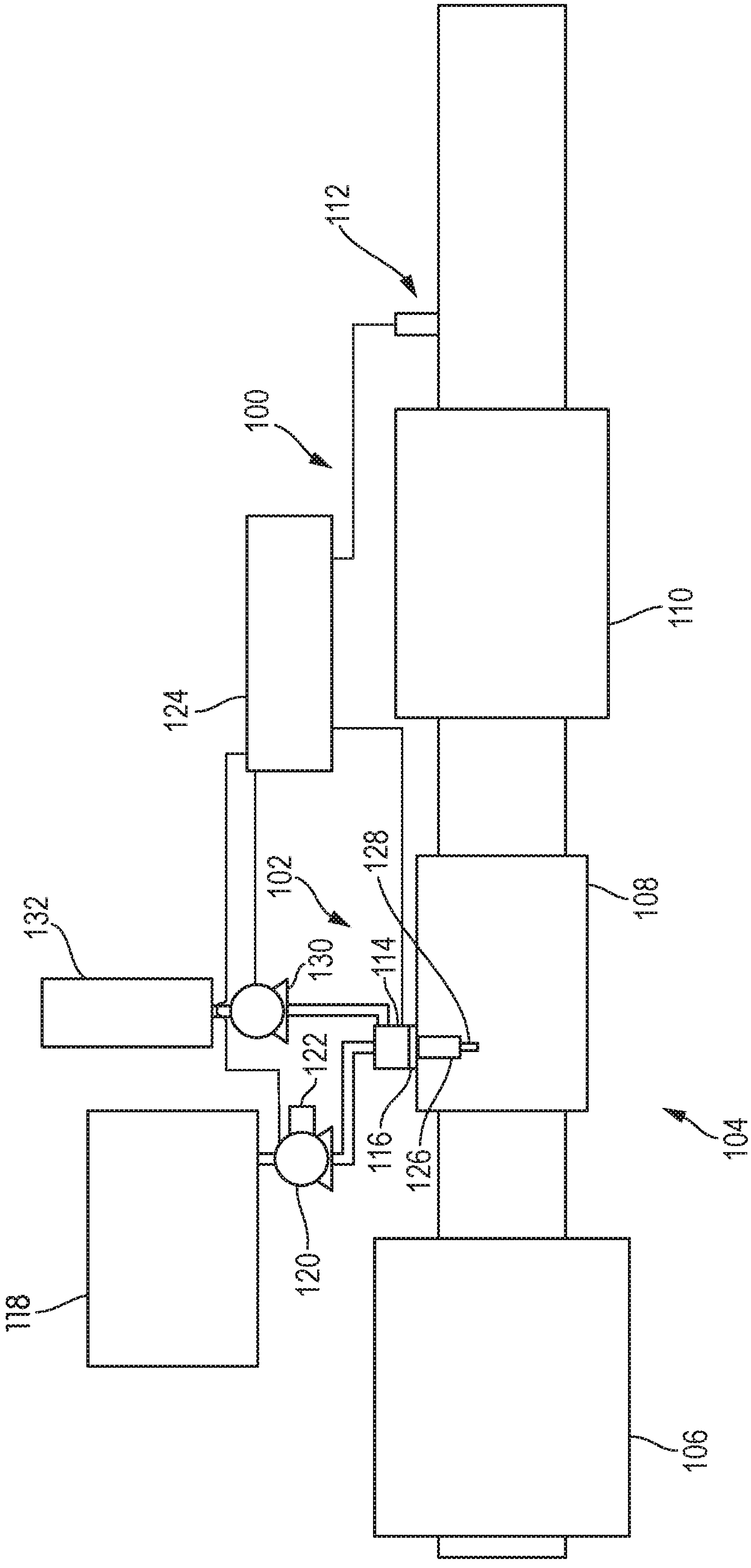
(57) **ABSTRACT**

A dosing module control system includes a central controller, a flow observer, and a switching doser controller. The central controller is configured to obtain a target flow rate and a target pressure. The flow observer is configured to determine a flow rate gain. The switching doser controller is configured to communicate with the central controller and the flow observer. The switching doser controller is configured to receive the target flow rate and the target pressure from the central controller, receive the flow rate gain from the flow observer, determine a compensated flow rate based on the target flow rate, the target pressure, and the flow rate gain, and determine at least one of an injector duty cycle associated with the determined compensated flow rate, or a pump frequency associated with the determined compensated flow rate. The pump is configured to communicate with the switching doser controller.

20 Claims, 5 Drawing Sheets

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100
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106

FIG. 1

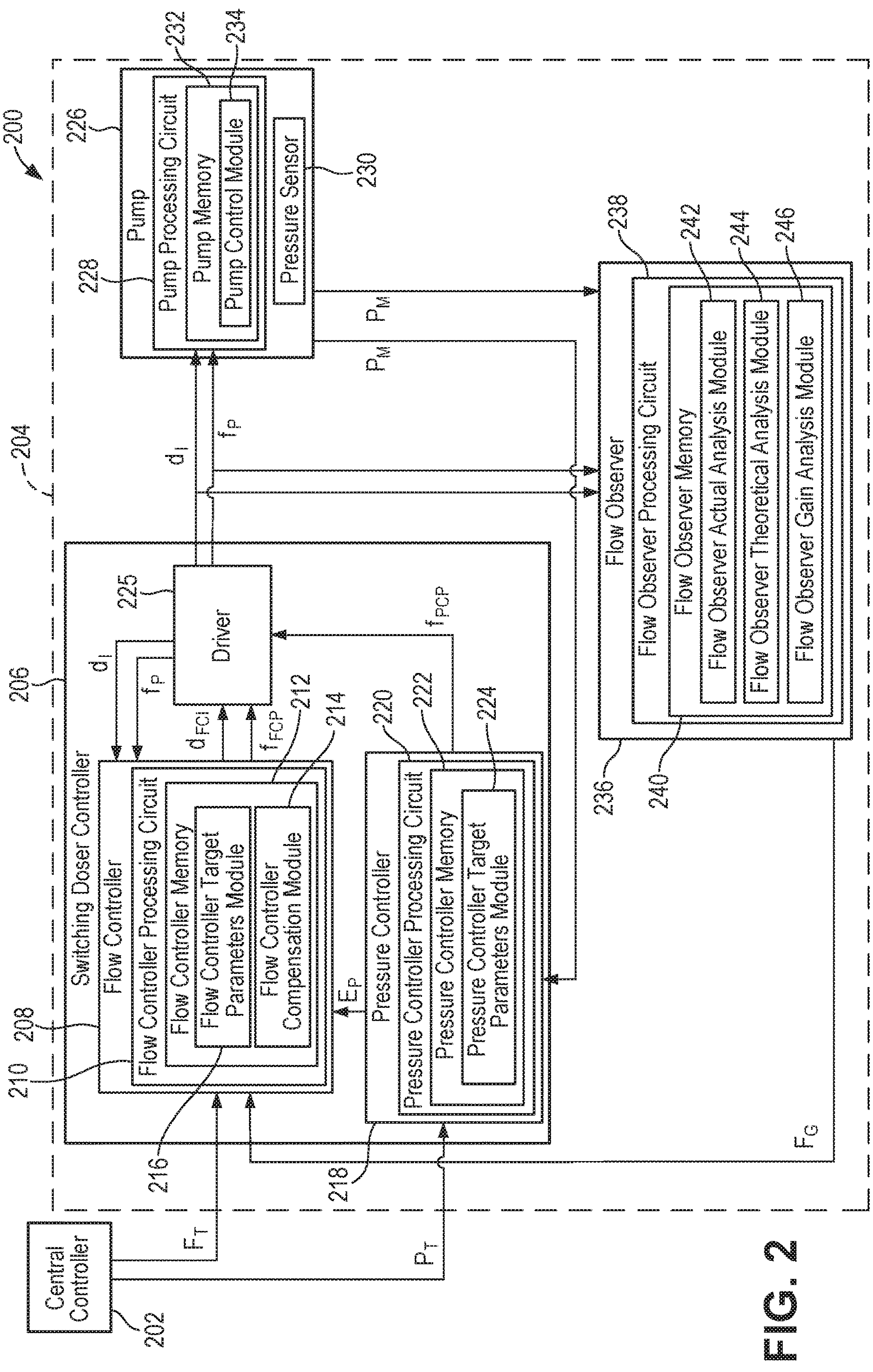
200
204
206
Switching Doser Controller
208
Flow Controller
210
Flow Controller Processing Circuit
212
Flow Controller Memory
216
Flow Controller Target Parameters Module
214
Flow Controller Compensation Module
225
Driver
d_I
f_P
d_{FCi}
f_{FCP}
f_{PCP}
E_P
218
Pressure Controller
220
Pressure Controller Processing Circuit
222
Pressure Controller Memory
224
Pressure Controller Target Parameters Module
226
Pump
228
Pump Processing Circuit
232
Pump Memory
234
Pump Control Module
230
Pressure Sensor
P_M
P_M
236
Flow Observer
238
Flow Observer Processing Circuit
240
Flow Observer Memory
242
Flow Observer Actual Analysis Module
244
Flow Observer Theoretical Analysis Module
246
Flow Observer Gain Analysis Module
F_G
202
Central Controller
F_T
P_T

FIG. 2

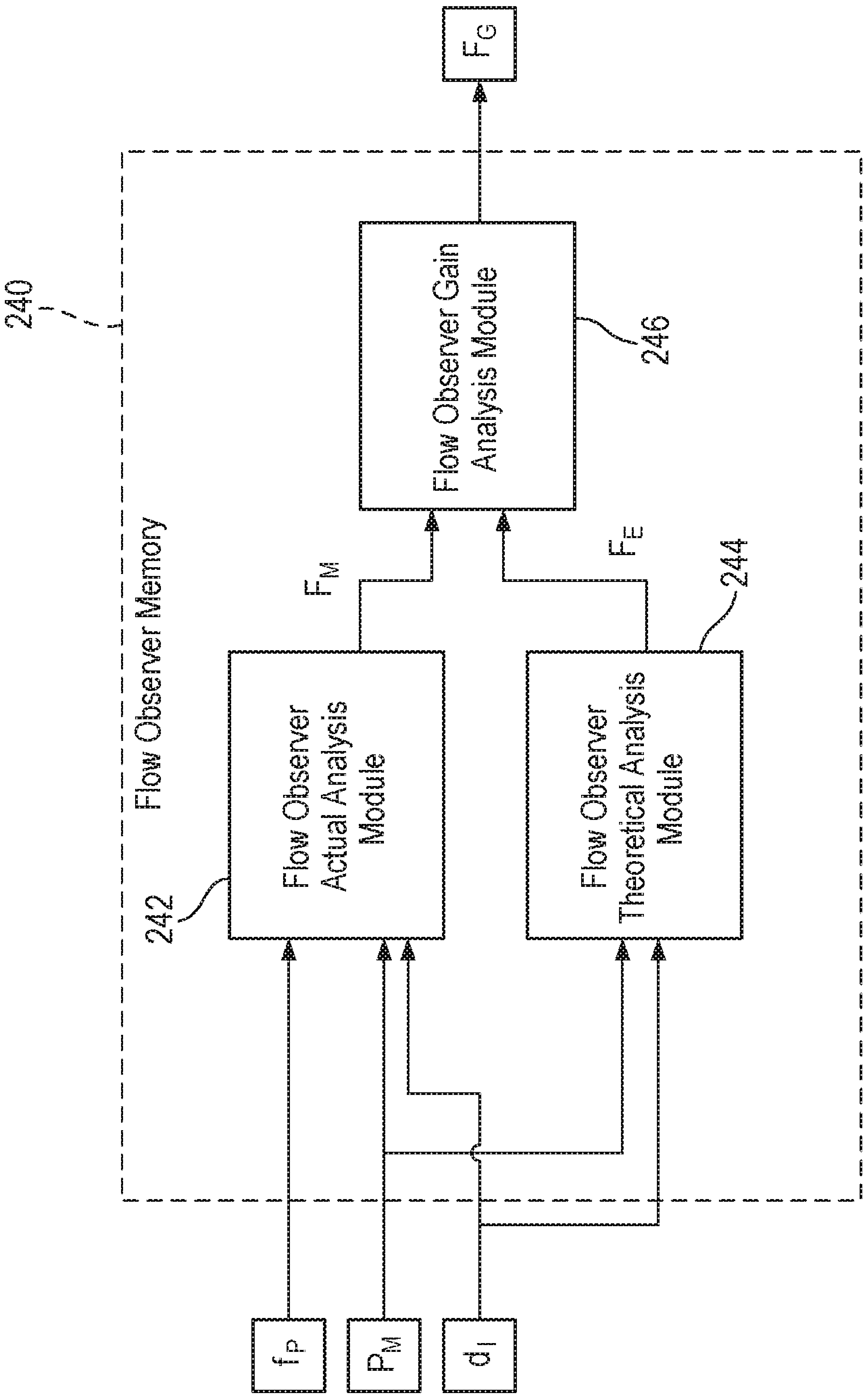
240
Flow Observer Memory
f_P
P_M
d_I
242
Flow Observer Actual Analysis Module
244
Flow Observer Theoretical Analysis Module
F_M
F_E
246
Flow Observer Gain Analysis Module
F_G

FIG. 3

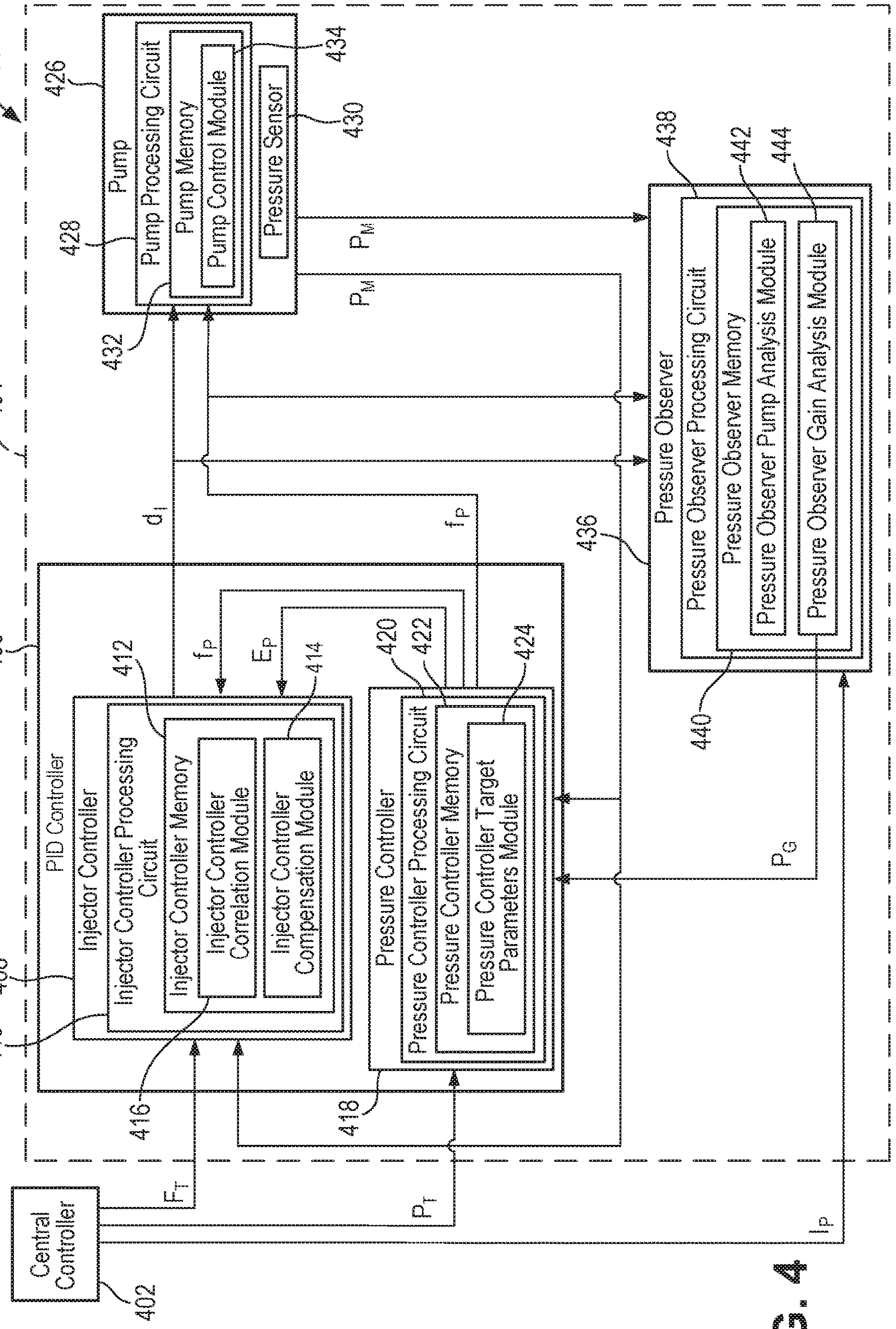
400
404
Pump
426
Pump Processing Circuit
428
Pump Memory
432
Pump Control Module
434
Pressure Sensor
430
P_M
P_M
PID Controller
406
Injector Controller
408
Injector Controller Processing Circuit
410
Injector Controller Memory
412
Injector Controller Correlation Module
416
Injector Controller Compensation Module
414
Pressure Controller
418
Pressure Controller Processing Circuit
420
Pressure Controller Memory
422
Pressure Controller Target Parameters Module
424
d_I
f_P
f_P
E_P
Pressure Observer
436
Pressure Observer Processing Circuit
438
Pressure Observer Memory
440
Pressure Observer Pump Analysis Module
442
Pressure Observer Gain Analysis Module
444
P_G
Central Controller
402
F_T
P_T
I_P

FIG. 4

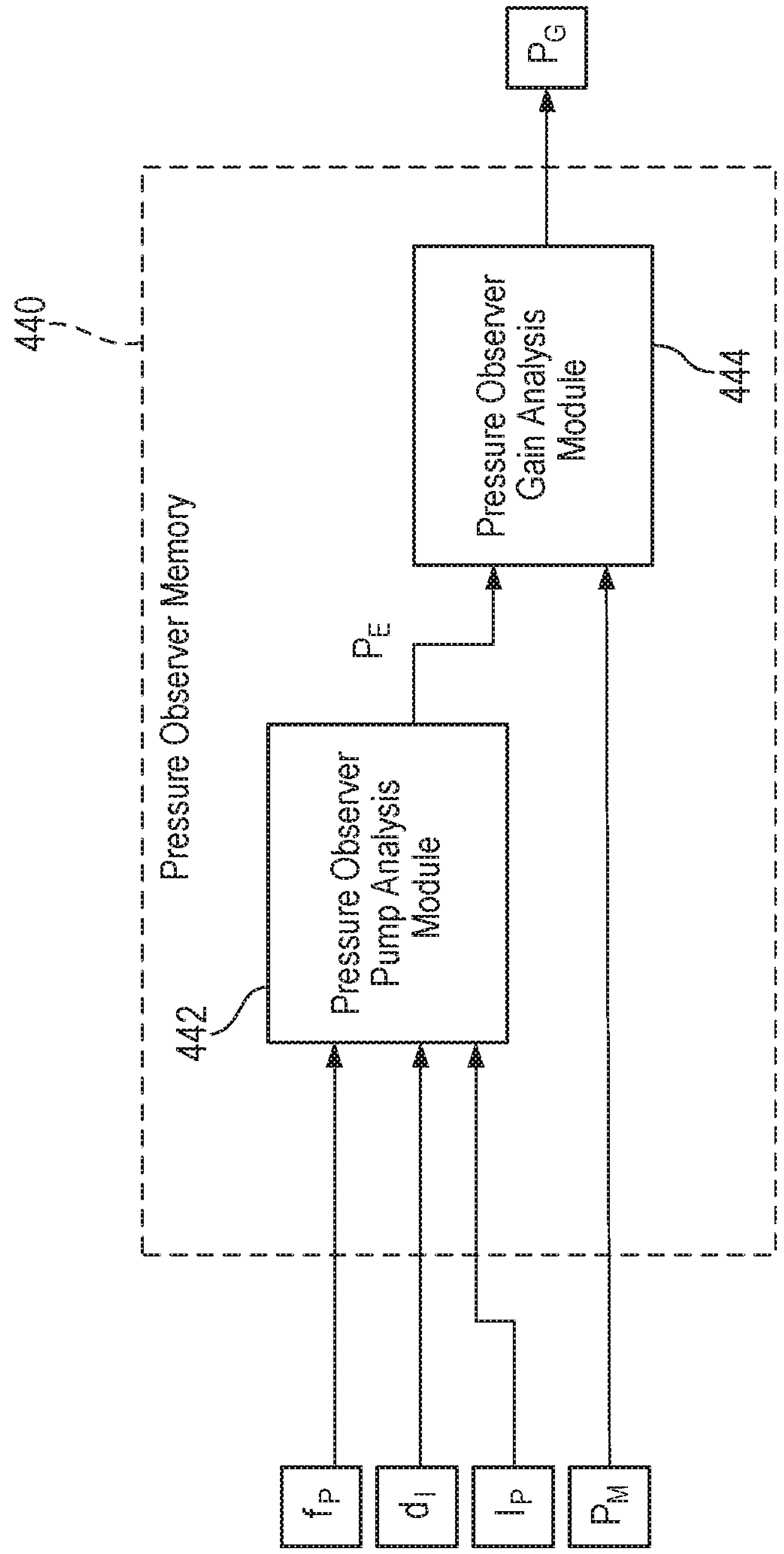
440
Pressure Observer Memory
442
Pressure Observer Pump Analysis Module
P_E
444
Pressure Observer Gain Analysis Module
P_G
f_P
d_I
I_P
P_M

FIG. 5

SYSTEMS AND METHODS FOR COMPENSATING A REDUCTANT DELIVERY SYSTEM IN AN AFTERTREATMENT SYSTEM OF AN INTERNAL COMBUSTION ENGINE

TECHNICAL FIELD

The present application relates generally to systems and methods for compensating for varying dimensions of an injector in a reductant delivery system in an aftertreatment system of an internal combustion engine.

BACKGROUND

For internal combustion engines, such as diesel engines, nitrogen oxide (NO_x) compounds may be emitted in the engine exhaust. To reduce NO_x emissions, a reductant may be dosed into the exhaust by a dosing system. The dosing system includes an injector through which the reductant is dosed into the exhaust.

SUMMARY

In the above-described systems, the dimensions of the injector influence performance of the dosing system. Injectors are typically manufactured such that the dimensions of each injector are contained within a tolerance. As a result, each injector may have different dimensions. A dosing system may include a pressure sensor that measures the pressure of the reductant immediately upstream of the injector. Based on this pressure, the dosing system may, for example, provide more or less reductant to the injector (e.g., by changing a speed of a pump, by opening or closing a valve, etc.). However, the pressure sensor is tuned (e.g., calibrated, etc.) by a manufacturer (e.g., during a testing process, etc.) according to the dimensions of the injector in order to ensure proper operation of the pressure sensor. Tuning of the pressure sensor increases the costs associated with the dosing system. Accordingly, it is desirable to compensate for the dimensions of an injector without using a tuning process that tailors a sensor to the dimensions of the injector, thereby avoiding the added cost associated with the tuning process.

In one embodiment, a dosing module control system includes a central controller, a flow observer, and a switching doser controller. The central controller is configured to obtain a target flow rate and a target pressure. The flow observer is configured to determine a flow rate gain. The switching doser controller is configured to communicate with the central controller and the flow observer. The switching doser controller is configured to receive the target flow rate and the target pressure from the central controller, receive the flow rate gain from the flow observer, determine a compensated flow rate based on the target flow rate, the target pressure, and the flow rate gain, and determine at least one of an injector duty cycle associated with the determined compensated flow rate, or a pump frequency associated with the determined compensated flow rate. The pump is configured to communicate with the switching doser controller. The pump is configured to receive the at least one of the injector duty cycle or the pump frequency from the switching doser controller and to operate based on the at least one of the determined injector duty cycle or the determined pump frequency to provide reductant at the compensated flow rate.

In another embodiment, a dosing module control system includes a central controller, a pressure observer, a proportional-integral-derivative (PID) controller, and a pump. The central controller is configured to obtain a target flow rate and a target pressure. The pressure observer is configured to determine a pressure gain. The PID controller is configured to communicate with the central controller and the pressure observer. The PID controller is configured to receive the target flow rate and the target pressure from the central controller, receive the pressure gain from the pressure observer, determine a compensated flow rate based on the target flow rate, the target pressure, and the pressure gain, and determine at least one of an injector duty cycle associated with the compensated flow rate, or a pump frequency associated with the compensated flow rate. The pump is configured to communicate with the PID controller. The pump is configured to receive the at least one of the injector duty cycle or the pump frequency from the PID controller and to operate based on the at least one of the injector duty cycle or the pump frequency to provide reductant at the compensated flow rate.

BRIEF DESCRIPTION OF THE DRAWINGS

The details of one or more implementations are set forth in the accompanying drawings and the description below. Other features, aspects, and advantages of the disclosure will become apparent from the description, the drawings, and the claims, in which:

FIG. **1** is a block schematic diagram of an example aftertreatment system;

FIG. **2** is a block schematic diagram of an example dosing module control system for use in an aftertreatment system, such as the example aftertreatment system shown in FIG. **1**;

FIG. **3** is a detailed view of a portion of the example dosing module control system shown in FIG. **2**;

FIG. **4** is a block schematic diagram of an example dosing module control system for use in an aftertreatment system, such as the example aftertreatment system shown in FIG. **1**; and

FIG. **5** is a detailed view of a portion of the example dosing module control system shown in FIG. **4**.

It will be recognized that some or all of the figures are schematic representations for purposes of illustration. The figures are provided for the purpose of illustrating one or more implementations with the explicit understanding that they will not be used to limit the scope or the meaning of the claims.

DETAILED DESCRIPTION

Following below are more detailed descriptions of various concepts related to, and implementations of, methods, apparatuses, and systems compensating a reductant delivery system in an aftertreatment system of an internal combustion engine. The various concepts introduced above and discussed in greater detail below may be implemented in any of numerous ways, as the described concepts are not limited to any particular manner of implementation. Examples of specific implementations and applications are provided primarily for illustrative purposes.

I. Overview

Internal combustion engines (e.g., diesel internal combustion engines, etc.) produce exhaust gases that are often treated by a dosing module within an aftertreatment system. Dosing modules typically treat exhaust gases using a reductant. The reductant is typically provided from the dosing module into a dosing lance which distributes (e.g., doses, etc.) the reductant into an exhaust stream within an exhaust component.

Dosing modules include pumps which propel the reductant from a reductant tank into the dosing lance. Dosing modules may include a sensor that measures a pressure of the reductant within the pump, upstream of the pump, or downstream of the pump. Dosing modules may include a controller that receives the pressure from the sensor and is configured to control the pump according to the pressure. The sensors need to be tuned on an application by application basis, due to variations in injector dimensions, in order to optimize operation of the pump. This tuning requires a specialized process where workers perform various tuning operations. Accordingly, tuning represents a recognizable cost associated with the dosing modules.

Implementations described herein relate to a dosing module control systems that are configured to operate the pump in an optimal manner without a tuning process. The dosing module control system includes a controller that provides an injector duty cycle and/or a pump frequency to the pump to control operation of the pump. The controller is configured to determine the injector duty cycle and/or pump frequency continuously and dynamically change the injector duty cycle and/or pump frequency based on operation of the pump. The dosing module control system includes a flow observer and/or a pressure observer that monitors a pressure of the reductant associated with the pump and determines a pressure gain and/or a flow rate gain which is provided to the controller and utilized in determining the injector duty cycle and/or pump frequency. The dosing module control systems described herein are capable of optimizing operation of a pump on a continuous basis without regard for injector dimensions and without the need for a tuning process and the additional costs associated therewith.

II. Overview of Aftertreatment System

FIG. **1** depicts an aftertreatment system **100** having an example reductant delivery system **102** for an exhaust system **104**. The aftertreatment system **100** includes a particulate filter (e.g., a diesel particulate filter (DPF) **106**), the reductant delivery system **102**, a decomposition chamber **108** (e.g., reactor, reactor pipe, etc.), a SCR catalyst **110**, and a sensor **112**.

The DPF **106** is configured to (e.g., structured to, able to, etc.) remove particulate matter, such as soot, from exhaust gas flowing in the exhaust system **104**. The DPF **106** includes an inlet, where the exhaust gas is received, and an outlet, where the exhaust gas exits after having particulate matter substantially filtered from the exhaust gas and/or converting the particulate matter into carbon dioxide. In some implementations, the DPF **106** may be omitted.

The decomposition chamber **108** is configured to convert a reductant into ammonia. The reductant may be, for example, urea, diesel exhaust fluid (DEF), Adblue®, an urea water solution (UWS), an aqueous urea solution (e.g., AUS32, etc.), and other similar fluids. The decomposition chamber **108** includes a reductant delivery system **102** having a doser or dosing module **114** configured to dose the reductant into the decomposition chamber **108** (e.g., via an injector). In some implementations, the reductant is injected upstream of the SCR catalyst **110**. The reductant droplets then undergo the processes of evaporation, thermolysis, and hydrolysis to form gaseous ammonia within the exhaust system **104**. The decomposition chamber **108** includes an inlet in fluid communication with the DPF **106** to receive the exhaust gas containing NO_x emissions and an outlet for the exhaust gas, NO_x emissions, ammonia, and/or reductant to flow to the SCR catalyst **110**.

The decomposition chamber **108** includes the dosing module **114** mounted to the decomposition chamber **108** such that the dosing module **114** may dose the reductant into the exhaust gases flowing in the exhaust system **104**. The dosing module **114** may include an insulator **116** interposed between a portion of the dosing module **114** and the portion of the decomposition chamber **108** on which the dosing module **114** is mounted. The dosing module **114** is fluidly coupled to (e.g., fluidly configured to communicate with, etc.) a reductant source **118**. The reductant source **118** may include multiple reductant sources **118**. The reductant source **118** may be, for example, a diesel exhaust fluid tank containing Adblue®.

A supply unit or reductant pump **120** is used to pressurize the reductant from the reductant source **118** for delivery to the dosing module **114**. In some embodiments, the reductant pump **120** is pressure controlled (e.g., controlled to obtain a target pressure, etc.). The reductant pump **120** includes a filter **122**. The filter **122** filters (e.g., strains, etc.) the reductant prior to the reductant being provided to internal components (e.g., pistons, vanes, etc.) of the reductant pump **120**. For example, the filter **122** may inhibit or prevent the transmission of solids (e.g., solidified reductant, contaminants, etc.) to the internal components of the reductant pump **120**. In this way, the filter **122** may facilitate prolonged desirable operation of the reductant pump **120**. In some embodiments, the reductant pump **120** is coupled to a chassis of a vehicle associated with the aftertreatment system **100**.

The dosing module **114** and reductant pump **120** are also electrically or communicatively coupled to a controller **124**. The controller **124** is configured to control the dosing module **114** to dose the reductant into the decomposition chamber **108**. The controller **124** may also be configured to control the reductant pump **120**. The controller **124** may include a microprocessor, an application-specific integrated circuit (ASIC), a field-programmable gate array (FPGA), etc., or combinations thereof. The controller **124** may include memory, which may include, but is not limited to, electronic, optical, magnetic, or any other storage or transmission device capable of providing a processor, ASIC, FPGA, etc. with program instructions. This memory, as well as the flow controller memory **212**, the pressure controller memory **222**, the pump memory **232**, and the flow observer memory **240**, may include a memory chip, Electrically Erasable Programmable Read-Only Memory (EEPROM), Erasable Programmable Read Only Memory (EPROM), flash memory, or any other suitable memory from which the associated controller can read instructions. The instructions may include code from any suitable programming language.

The SCR catalyst **110** is configured to assist in the reduction of NO_x emissions by accelerating a NO_x reduction process between the ammonia and the NO_x of the exhaust gas into diatomic nitrogen, water, and/or carbon dioxide. The SCR catalyst **110** includes an inlet in fluid communication with the decomposition chamber **108** from which exhaust gas and reductant are received and an outlet in fluid communication with an end of the exhaust system **104**.

The exhaust system **104** may further include an oxidation catalyst (e.g., a diesel oxidation catalyst (DOC)) in fluid communication with the exhaust system **104** (e.g., downstream of the SCR catalyst **110** or upstream of the DPF **106**) to oxidize hydrocarbons and carbon monoxide in the exhaust gas.

In some implementations, the DPF **106** may be positioned downstream of the decomposition chamber **108**. For instance, the DPF **106** and the SCR catalyst **110** may be combined into a single unit. In some implementations, the dosing module **114** may instead be positioned downstream of a turbocharger or upstream of a turbocharger.

The sensor **112** may be coupled to the exhaust system **104** to detect a condition of the exhaust gas flowing through the exhaust system **104**. In some implementations, the sensor **112** may have a portion disposed within the exhaust system **104**; for example, a tip of the sensor **112** may extend into a portion of the exhaust system **104**. In other implementations, the sensor **112** may receive exhaust gas through another conduit, such as one or more sample pipes extending from the exhaust system **104**. While the sensor **112** is depicted as positioned downstream of the SCR catalyst **110**, it should be understood that the sensor **112** may be positioned at any other position of the exhaust system **104**, including upstream of the DPF **106**, within the DPF **106**, between the DPF **106** and the decomposition chamber **108**, within the decomposition chamber **108**, between the decomposition chamber **108** and the SCR catalyst **110**, within the SCR catalyst **110**, or downstream of the SCR catalyst **110**. In addition, two or more sensors **112** may be utilized for detecting a condition of the exhaust gas, such as two, three, four, five, or six sensors **112** with each sensor **112** located at one of the aforementioned positions of the exhaust system **104**.

The dosing module **114** includes a dosing lance assembly **126**. The dosing lance assembly **126** includes a delivery conduit (e.g., delivery pipe, delivery hose, etc.). The delivery conduit is fluidly coupled to the reductant pump **120**. The dosing lance assembly **126** includes at least one injector **128**. The injector **128** is configured to dose the reductant into the exhaust gases (e.g., within the decomposition chamber **108**, etc.). While not shown, it is understood that the dosing module **114** may include a plurality of injectors **128**.

The reductant delivery system **102** also includes an air pump **130**. The air pump **130** draws air from an air source **132** (e.g., air intake, etc.). Additionally, the air pump **130** provides the air to the dosing module **114** via a conduit. The dosing module **114** is configured to mix the air and the reductant into an air-reductant mixture. The dosing module **114** is further configured to provide the air-reductant mixture into the decomposition chamber **108**.

III. Example Doser Control System with Switching Doser Controller and Flow Observer

FIG. **2** illustrates an example dosing module control system **200**. The dosing module control system **200** is implemented with at least one dosing module (e.g., the dosing module **114**, etc.) in an aftertreatment system (e.g., the aftertreatment system **100**, etc.) of an internal combustion engine system. For example, the dosing module control system **200** may be implemented with a plurality (e.g., two, three, four, etc.) of dosing modules.

The dosing module control system **200** includes a central controller **202**. The central controller **202** may be, for example, an engine control unit (ECU), an aftertreatment controller, or other similar controller associated with an internal combustion engine and/or aftertreatment system. The dosing module control system **200** includes a doser compensation system **204**. As will be explained in more detail herein, the doser compensation system **204** functions to receive a target flow rate from the central controller **202**, analyze parameters associated with a pump of a doser, and implement a flow rate gain which facilitates optimized operation of the pump.

The doser compensation system **204** includes a switching doser controller **206**. The switching doser controller **206** includes a flow controller **208**. The flow controller **208** is configured to communicate with (e.g., is communicably coupled to, is electrically configured to communicate with, is electrically coupled to, etc.) the central controller **202**. The flow controller **208** is configured to receive a target flow rate F_T from the central controller **202**. The target flow rate F_T may be a mass flow rate, a volumetric flow rate, or other similar flow rates. As will be explained in more detail herein, the flow controller **208** is configured to selectively modify the target flow rate F_T to obtain a compensated flow rate F_C. The compensated flow rate F_C reflects a calculated variation in the target flow rate F_T based on operation of a pump (e.g., the reductant pump **120**, etc.). Once the compensated flow rate F_C has been obtained, the switching doser controller **206** causes the pump (e.g., the reductant pump **120**, etc.) to operate (e.g., to change a state of the pump, etc.) according to the compensated flow rate F_C (e.g., to output reductant at the compensated flow rate F_C, etc.) thereby increasing the desirability of the pump.

The switching doser controller **206** is operable in a first state (e.g., disabled state, off state, deactivated state, etc.), where the compensated flow rate F_C is equal to the target flow rate F_T, and a second state (e.g., enabled state, on state, activated state, etc.), where the compensated flow rate F_C is a function of the target flow rate F_T and an average flow rate gain F_{GAvg}, which is a function of a flow rate gain F_G. As will be explained in more detail herein, the flow rate gain F_G is determined based on operation of a pump (e.g., the reductant pump **120**, etc.) and the average flow rate gain F_{GAvg} is determined using discrete time integration. In one example, the switching doser controller **206** may be in the first state such that the compensated flow rate F_C is equal to the target flow rate F_T upon start-up of an internal combustion engine (e.g., at the first time step, etc.) having the dosing module control system **200**.

The flow controller **208** includes a flow controller processing circuit **210** which further includes a flow controller memory **212**. The flow controller memory **212** includes a flow controller compensation module **214** and a flow controller target parameters module **216**. The flow controller compensation module **214** is configured to control the state of the switching doser controller **206** (e.g., modulate the switching doser controller **206** between the first state and the second state, etc.). Once the flow controller **208** determines the compensated flow rate F_C, the flow controller **208** utilizes the compensated flow rate F_C to produce a flow controller injector duty cycle d_{FCI} and a flow controller pump frequency f_{FCP}. The flow controller injector duty cycle d_{FCI} is a duty cycle determined by the flow controller **208** for at least one injector (e.g., the injector **128**, etc.) of a reductant delivery system (e.g., the reductant delivery system **102**, etc.) having the dosing module control system **200**. The flow controller pump frequency f_{FCP} is a pump frequency determined from the flow controller **208** for a pump (e.g., the reductant pump **120**, etc.) of the dosing module control system **200**.

The switching doser controller **206** also includes a pressure controller **218**. The pressure controller **218** is configured to receive a target pressure P_T from the central controller **202** and to receive a measured pressure P_M. The target pressure P_T is a target (e.g., desired, theoretical, etc.) pressure associated with a pump (e.g., the reductant pump **120**, etc.) of the dosing module control system **200**. The measured pressure P_M is a measured (e.g., actual, etc.) pressure associated with a pump (e.g., the reductant pump **120**, etc.) of the dosing module control system **200**. The measured pressure P_M may be an average of a set of pressures (e.g., an average of a set of pressures obtained over an interval of time, an average of a set of a number of pressure readings, etc.). The pressure controller **218** includes a pressure controller processing circuit **220** which further includes a pressure controller memory **222**. The pressure controller memory **222** includes a pressure controller target parameters module **224**. The pressure controller **218** utilizes the target pressure P_T to produce a pressure controller pump frequency f_{PCP}. The pressure controller pump frequency f_{FCP} is a frequency associated with a pump (e.g., the reductant pump **120**, etc.) of the dosing module control system **200** as measured by the pressure controller **218**.

The doser compensation system **204** also includes a driver **225**. The driver **225** is configured to receive the flow controller injector duty cycle d_{FCI} and the flow controller pump frequency f_{FCP} from the flow controller **208**, receive the pressure controller pump frequency f_{PCP} from the pressure controller **218**, and produce an injector duty cycle d_I and a pump frequency G. The injector duty cycle d_I is a percentage of time over a target duration in which the injector (e.g., the injector **128**, etc.) is activated and dosing the reductant (e.g., into the exhaust gases, etc.). The pump frequency f_P is a frequency at which a pump (e.g., the reductant pump **120**, etc.) is to operate (e.g., a number of strokes of a cylinder within the pump per second, a number of revolutions of an impeller within the pump per second, etc.).

The doser compensation system **204** also includes a pump **226** (e.g., positive displacement pump, centrifugal pump, etc.). In an example embodiment, the pump **226** may be a piston pump P1300 from Thomas Magnete GmbH. The pump **226** is part of the dosing module (e.g., the dosing module **114**, etc.) that the dosing module control system **200** is implemented with. The pump **226** controls the flow of reductant from the dosing module and therefore controls the amount of reductant that is dosed into an exhaust component.

The pump **226** includes a pump processing circuit **228** and a pressure sensor **230**. The pressure sensor **230** is configured to measure the pressure of the reductant provided by the pump **226** (e.g., at an outlet of the pump **226**, etc.) and/or the pressure of the reductant provided to the pump **226** (e.g., at an inlet of the pump **226**, etc.). The pump processing circuit **228** includes a pump memory **232** which further includes a pump control module **234**. The pump **226** is configured to receive the injector duty cycle d_I and pump frequency f_P from the driver **225** and alter operation of the pump **226** accordingly. For example, as the pump frequency f_P increases, the pump **226** may cause an impeller of the pump **226** to spin faster. The pump **226** is configured to provide the measured pressure P_M. As the injector duty cycle d_I and pump frequency f_P change, the measured pressure P_M correspondingly changes.

The doser compensation system **204** also includes a flow observer **236**. The flow observer includes a flow observer processing circuit **238** which further includes a flow observer memory **240**. The flow observer memory **240** includes a flow observer actual analysis module **242**, a flow observer theoretical analysis module **244**, and a flow observer gain analysis module **246**. The flow observer **236** is configured to receive the injector duty cycle d_I and pump frequency f_P from the driver **225**, receive the measured pressure P_M, and produce the flow rate gain F_G.

FIG. **3** illustrates the flow observer memory **240** in greater detail. The flow observer actual analysis module **242** is configured to receive the pump frequency f_P, the measured pressure P_M, and the injector duty cycle d_I. The flow observer actual analysis module **242** is configured to produce a measured flow F_M. The measured flow F_M is a measured flow rate of reductant through and/or into the pump **226**. The flow observer theoretical analysis module **244** is configured to receive the measured pressure P_M and the injector duty cycle d_I and produce an estimated flow F_E. The estimated flow F_E is an estimated (e.g., calculated, determined, etc.) flow rate of reductant through and/or into the pump **226**. The flow observer gain analysis module **246** is configured to receive the measured flow F_M and the estimated flow F_E and produce the flow rate gain F_G. The flow rate gain F_G is a dimensionless factor that represents a comparison between the measured flow F_M and the estimated flow F_E.

After receiving the pump frequency f_P, the flow observer actual analysis module **242** is configured to correlate the pump frequency f_P to a correlated frequency flow C_{FF}. For example, the flow observer actual analysis module **242** may utilize a lookup table or datasheet provided by a manufacturer of the pump **226** to correlate the pump frequency G to the correlated frequency flow C_{FF}. The correlated frequency flow C_{FF} is used to compute the measured flow F_M. The correlation of the pump frequency f_P to the correlated frequency flow C_{FF} is also based on the measured pressure P_M. In an example embodiment, the correlation of the pump frequency f_P to the correlated frequency flow C_{FF} may be given by

$$C_{FF} = \frac{0.325\, f_P}{3600} \tag{1}$$

where the measured pressure P_M is 0 bar and

$$C_{FF} = \frac{0.2875\, f_P}{3600} \tag{2}$$

where the measured pressure P_M is 8 bar. Accordingly, the correlation of the pump frequency f_P to a correlated frequency flow C_{FF} may be given by

$$C_{FF} = \frac{(0.325 - 0.0046875\, P_M) f_P}{3600} \tag{3}$$

After receiving the measured pressure P_M, the flow observer actual analysis module **242** is configured to correlate the measured pressure P_M to a correlated pressure flow C_{PF}. For example, the flow observer actual analysis module **242** may utilize a lookup table or datasheet provided by a manufacturer of the pump **226** to correlate the measured pressure P_M to the correlated pressure flow C_{PF}. The correlated pressure flow C_{PF} is used to compute the measured flow F_M. In an example embodiment, the correlation of the measured pressure P_M to the correlated pressure flow C_{PF} may be given by

$$C_{PF} = \frac{7.6}{3600}\left[\frac{L}{s}\right] \tag{4}$$

where the measured pressure P_M is 0 bar and

$$C_{PF} = \frac{6.9}{3600}\left[\frac{L}{s}\right] \tag{5}$$

where the measured pressure P_M is 8 bar. Accordingly, the correlation of the measured pressure P_M to a correlated pressure flow C_{PF} may be given by

$$C_{PF} = (0.0125\ P_M + 1) * \frac{6.9}{3600} \tag{6}$$

The flow observer actual analysis module **242** is also configured to correlate the injector duty cycle d_I to a correlated injector factor C_{IF}. The correlated injector factor C_{IF} is determined by

$$C_{IF} = \frac{d_I}{100} \tag{7}$$

In an example embodiment, the measured flow F_M is then determined by

$$F_M = \left(\frac{C_{FF} + C_{PF}}{2}\right) C_{IF} \tag{8}$$

although other similar functions of the correlated frequency flow C_{FF}, the correlated pressure flow C_{PF}, and correlated injector factor C_{IF} may be utilized to determine the measured flow F_M. In these ways, the flow observer actual analysis module **242** functions as a tuning linear pump flow model.

After receiving the injector duty cycle d_I and the measured pressure P_M, the flow observer theoretical analysis module **244** is configured to utilize the injector duty cycle d_I and the measured pressure P_M to compute the estimated flow F_E. The flow observer theoretical analysis module **244** utilizes a look-up table or datasheet provided by a manufacturer of the pump **226** to correlate the injector duty cycle d_I and the measured pressure P_M to the estimated flow F_E. The flow observer theoretical analysis module **244** communicates with the pump **226** to cause the pump **226** to operate at a target injector duty cycle d_{TI1}, thereby causing the pump **226** to obtain a target measured pressure P_{TM}. The flow observer theoretical analysis module **244** then computes the estimated flow F_{E1} for the target injector duty cycle d_{TI}. The flow observer theoretical analysis module **244** then computes the estimated flow F_{E2} for a different target injector duty cycle d_{TI2}. After a target number (e.g., two, three, four, etc.) of computed estimated flows F_{E1}, F_{E2} have been computed, the estimated flow F_E is computed by taking the average of the computed estimated flows F_{E1}, F_{E2}. In an example embodiment, the flow observer theoretical analysis module **244** controls the injector duty cycle d_I using a proportional-integral-derivative (PID) controller. In these ways, the flow observer actual analysis module **242** functions as a tuning pressure to flow model.

The flow observer gain analysis module **246** is configured to compute the flow rate gain F_G based on the measured flow F_M and the estimated flow F_E. The measured flow F_M is first passed through a saturation filter which imposes an upper limit and lower limit on the measured flow F_M. In other words, if the measured flow F_M is above the upper limit the measured flow F_M will be set to the upper limit by the saturation filter and the measured flow F_M will be set to the lower limit by the saturation filter if the measured flow F_M is below the lower limit. An initial flow rate gain F_{IG} is then computed by

$$F_{IG} = \frac{F_E}{F_M} \tag{9}$$

The initial flow rate gain F_{IG} is then passed through a time constant filter (e.g., high pass filter, low pass filter, etc.) to produce the flow rate gain F_G. In an example embodiment, this time constant filter is a first order two second filter that executes at 10 Hertz (Hz) (e.g., when the pump frequency f_P is 10 Hz, etc.). The time constant filter may be

$$F_G = \frac{num(F_{IG})}{1 - 0.995 F_{IG}^{-1}} \tag{10}$$

where $num(F_{IG})$ is the real component (e.g., as opposed to any imaginary component, etc.) of the initial flow rate gain F_{IG}. The flow rate gain F_G is then passed through a saturation filter which imposes an upper limit and lower limit on the flow rate gain F_G. In other words, if the flow rate gain F_G is above the upper limit the flow rate gain F_G will be set to the upper limit by the saturation filter and the flow rate gain F_G will be set to the lower limit by the saturation filter if the flow rate gain F_G is below the lower limit. In an example embodiment, the upper limit is 1.4 and the lower limit is 0.6. In various embodiments, the average of the upper limit and the lower limit does not equal 1.

Once the flow rate gain F_G has been computed by the flow observer gain analysis module **246**, the flow rate gain F_G is provided to the flow controller **208**, and the process of determining the compensated flow rate F_C beings again. This operation may be run in a continuous loop such that the pump **226** continues to operate desirably. In this way, the dosing module control system **200** may optimize operation of the pump **226** according to dimensions of a specific injector associated with the dosing module control system **200**. Additionally, the dosing module control system **200** may be utilized to perform on-board or remote diagnostics. For example, the doser compensation system **204** may communicate with an external system (e.g., a laptop, a computer, a mobile phone, etc.) and transmit, for example, the measured pressure P_M, the flow rate gain F_G, the injector duty cycle d_I, the pump frequency f_P, and the pressure error E_P to the external system.

The central controller **202**, the flow controller processing circuit **210**, the pressure controller processing circuit **220**, the driver **225**, the pump processing circuit **228**, and/or the flow observer processing circuit **238** may include a microprocessor, an ASIC, a FPGA, etc., or combinations thereof. The central controller **202** and/or the driver **225** may include memory, which may include, but is not limited to, electronic, optical, magnetic, or any other storage or transmission device capable of providing a processor, ASIC, FPGA, etc. with program instructions. The memory may include a memory chip, EEPROM, EPROM, flash memory, or any other suitable memory from which the associated controller can read instructions. The instructions may include code from any suitable programming language.

The doser compensation system **204** may be located separate from the central controller **202**. For example, the central controller **202** may be located proximate a front end of a vehicle (e.g., in an engine bay, in a cab, etc.) and the doser compensation system **204** may be located proximate a rear end of a vehicle (e.g., in a cargo bay, in a frame compartment, etc.).

The driver **225** is configured to provide the injector duty cycle d_I and the pump frequency f_P to the flow controller **208**. Additionally, the pressure controller **218** is configured to compare the target pressure P_T and the measured pressure P_M to determine a pressure error E_P. The pressure controller **218** is also configured to provide the pressure error E_P to the flow controller **208**.

The switching doser controller **206** is configured to switch between the first state, where the compensated flow rate F_C is equal to the target flow rate F_T, and the second state, where the compensated flow rate F_C is a function of the target flow rate F_T and an average flow rate gain F_{GAvg}, which is a function of a flow rate gain F_G. In an example embodiment, the switching doser controller **206** is configured to operate in the first state when an internal combustion engine associated with the dosing module control system **200** is not powered and when the internal combustion engine is operating at conditions other than steady-state (e.g., warm up, cool down, etc.). In this embodiment, the switching doser controller **206** is configured to operate in the second state when the internal combustion engine is operating at steady-state and has been operating at steady state for an amount of time t greater than a target amount of time t_{Target} (e.g., 20 seconds, 20 minutes, etc.). In this way, the target amount of time t_{Target} functions like a threshold. In an example embodiment, the target amount of time t_{Target} is 20 seconds.

The switching doser controller **206** may determine if the internal combustion engine is operating at steady-state by comparing a parameter to maximum and minimum values for that parameter, the maximum and minimum values defining a range of the parameter associated with operation of the internal combustion engine at steady state. In various embodiments, these parameters are the injector duty cycle d_I, the pump frequency f_P, and the pressure error E_P. Accordingly, the switching doser controller **206** may utilize any combination of the comparisons

$$d_{IMin}<d_I<d_{IMax} \tag{11}$$

$$f_{PMin}<f_P<f_{PMax} \tag{12}$$

$$E_{PMin}<E_P<E_{PMax} \tag{13}$$

to determine if the internal combustion engine is operating at steady state. Specifically, the switching doser controller **206** may determine that the internal combustion engine is operating at steady state if: the injector duty cycle d_I is greater than a minimum injector duty cycle d_{IMin} and less than a maximum injector duty cycle d_{IMax}; the pump frequency f_P is greater than a minimum pump frequency f_{PMin} and less than a maximum pump frequency f_{PMax}; and/or the pressure error E_P is greater than a minimum pressure error E_{PMin} and less than a maximum pressure error E_{PMax}. The switching doser controller **206** may perform these comparisons continuously (e.g., at each time step, etc.). For example, the switching doser controller **206** may perform these comparisons continuously while the internal combustion engine is operational and not perform these comparisons while the internal combustion engine is not operational.

As previously mentioned, the compensated flow rate F_C is a function of the average flow rate gain F_{GAvg}. The average flow rate gain F_{GAvg} is determined continuously once the switching doser controller **206** has been in the second state for an amount of time t greater than the target amount of time t_{Target}. For example, so long as the injector duty cycle d_I is greater than the minimum injector duty cycle d_{IMin} and less than the maximum injector duty cycle d_{IMax}, and the amount of time t is greater than the target amount of time t_{Target}, the average flow rate gain F_{GAvg} may be determined. Once the switching doser controller **206** switches from the second state back to the first state, the amount of time t is reset back to 0 but will restart (e.g., count from 0 upwards) once the switching doser controller **206** is in the second state again. In this way, the amount of time t may be thought of as recording an amount of time that the switching doser controller **206** has been in the second state at the present instance of the switching doser controller **206** being in the second state (e.g., rather than a total amount of time that the switching doser controller **206** has been in the second state without regard to whether or not the switching doser controller **206** has been in the first state since initially entering the second state, etc.).

The amount of time t is a discrete output from a discrete time integration, using a unit delay, of an actual amount of time t_{Actual} that the switching doser controller **206** has been in the second state. Like the amount of time t, the actual amount of time t_{Actual} is also reset back to 0 when the switching doser controller **206** enters the first state, but will restart once the switching doser controller **206** enters the second state. The unit delay is equal to the amount of time t at one time step prior (e.g., n−1, etc.) to the time step (e.g., n, etc.) at which the actual amount of time t_{Actual} is determined, where the amount of time t is greater than the target amount of time t_{Target}.

To determine the average flow rate gain F_{GAvg}, the flow rate gain F_G is first passed through a discrete time integration using the unit delay. The flow rate gain F_G is then divided by the amount of time t, without regard as to the target amount of time t_{Target}, to determine the average flow rate gain F_{GAvg}. However, the switching doser controller **206** only utilizes the average flow rate gain F_{GAvg} in computing the compensated flow rate F_C if the amount of time t is greater than the target amount of time t_{Target}.

IV. Example Doser Control System with PID Controller and Pressure Observer

FIG. **4** illustrates an example dosing module control system **400**. The dosing module control system **400** is implemented with at least one dosing module (e.g., the dosing module **114**, etc.) in an aftertreatment system (e.g., the aftertreatment system **100**, etc.) of an internal combustion engine system. For example, the dosing module control system **400** may be implemented with a plurality (e.g., two, three, four, etc.) of dosing modules.

The dosing module control system **400** includes a central controller **402**. The central controller **402** is similar to the central controller **202** previously described. The dosing module control system **400** includes a doser compensation system **404**. As will be explained in more detail herein, the doser compensation system **404** functions to receive a target flow rate from the central controller **402**, analyze parameters associated with a pump of a doser, and form a compensated flow rate which facilitates optimized operation of the pump.

The doser compensation system **404** includes a PID controller **406**. The PID controller **406** includes an injector controller **408**. The injector controller **408** is configured to communicate with (e.g., is communicably coupled to, is electrically configured to communicate with, is electrically coupled to, etc.) the central controller **402**. The injector controller **408** is configured to receive a target flow rate F_T from the central controller **402** and to receive a measured pressure P_M from a pump (e.g., the reductant pump **120**, etc.). The measured pressure P_M may be an average of a set of pressures (e.g., an average of a set of pressures obtained over an interval of time, an average of a set of a number of pressure readings, etc.). The target flow rate F_T may be a mass flow rate, a volumetric flow rate, or other similar flow rates. The measured pressure P_M may be a pressure of reductant entering the pump or a pressure of the reductant exiting the pump. As will be explained in more detail herein, the PID controller **406** is configured to selectively modify the target flow rate F_T to obtain a compensated flow rate F_C. The compensated flow rate F_C reflects a calculated variation in the target flow rate F_T based on operation of a pump (e.g., the reductant pump **120**, etc.). Once the compensated flow rate F_C has been obtained, the PID controller **406** causes the pump (e.g., the reductant pump **120**, etc.) to operate (e.g., to change a state of the pump, etc.) according to the compensated flow rate F_C (e.g., to output reductant at the compensated flow rate F_C, etc.) thereby increasing the desirability of the pump.

The PID controller **406** is operable in a first state (e.g., disabled state, off state, deactivated state, etc.), where the compensated flow rate F_C is equal to the target flow rate F_T, and a second state (e.g., enabled state, on state, activated state, etc.), where the compensated flow rate F_C is a function of the target flow rate F_T and an average pressure gain P_{GAvg}, which is a function of a pressure gain P_G. As will be explained in more detail herein, the pressure gain P_G is determined based on operation of a pump (e.g., the reductant pump **120**, etc.) and the average pressure gain P_{GAvg} is determined using discrete time integration. In one example, the PID controller **406** may be in the first state such that the compensated flow rate F_C is equal to the target flow rate F_T upon start-up of an internal combustion engine (e.g., at the first time step, etc.) having the dosing module control system **400**.

The injector controller **408** includes an injector controller processing circuit **410** which further includes an injector controller memory **412**. The injector controller memory **412** includes an injector controller compensation module **414** and an injector controller correlation module **416**. The injector controller compensation module **414** is configured to control the state of the PID controller **406** (e.g., modulate the PID controller **406** between the first state and the second state, etc.). The injector controller correlation module **416** is configured to correlate the target flow F_T and the measured pressure P_M with an injector duty cycle d_I. The injector duty cycle d_I is a percentage of time over a target duration in which an injector (e.g., the injector **128**, etc.) of the dosing module control system **400** is activated and dosing the reductant (e.g., into the exhaust gases, etc.). In an example embodiment, the injector controller correlation module **416** utilizes a lookup table or datasheet provided by a manufacturer of the pump (e.g., the reductant pump **120**, etc.) to correlate the target flow F_T and the measured pressure P_M with an injector duty cycle d_I.

The PID controller **406** also includes a pressure controller **418**. The pressure controller **418** is configured to receive a target pressure P_T from the central controller **402** and to receive the measured pressure P_M from the pump (e.g., the reductant pump **120**, etc.). The target pressure P_T is a target (e.g., desired, theoretical, etc.) pressure associated with the pump (e.g., the reductant pump **120**, etc.). The pressure controller **418** includes a pressure controller processing circuit **420** which further includes a pressure controller memory **422**. The pressure controller memory **422** includes a pressure controller target parameters module **424**. The pressure controller **418** utilizes the target pressure P_T to produce a pump frequency f_P. The pump frequency f_P is a frequency at which a pump (e.g., the reductant pump **120**, etc.) of the dosing module control system **400** is to operate (e.g., a number of strokes of a cylinder within the pump per second, a number of revolutions of an impeller within the pump per second, etc.).

The doser compensation system **404** also includes a pump **426** (e.g., positive displacement pump, centrifugal pump, etc.). In an example embodiment, the pump **426** may be a piston pump P1300 from Thomas Magnete GmbH. The pump **426** is part of the dosing module (e.g., the dosing module **114**, etc.) that the dosing module control system **400** is implemented with. The pump **426** controls the flow of reductant from the dosing module and therefore controls the amount of reductant that is dosed into an exhaust component.

The pump **426** includes a pump processing circuit **428** and a pressure sensor **430**. The pressure sensor **430** is configured to measure the pressure of the reductant provided by the pump **426** (e.g., at an outlet of the pump **426**, etc.) and/or the pressure of the reductant provided to the pump **426** (e.g., at an inlet of the pump **426**, etc.). The pump processing circuit **428** includes a pump memory **432** which further includes a pump control module **434**. The pump **426** is configured to receive the injector duty cycle d_I and pump frequency f_P from the injector controller **408** and alter operation of the pump **426** accordingly. For example, as the pump frequency f_P increases, the pump **426** may cause an impeller of the pump **426** to spin faster. The pump **426** is configured to provide the measured pressure P_M. As the injector duty cycle d_I and pump frequency f_P change, the measured pressure P_M correspondingly changes.

The doser compensation system **404** also includes a pressure observer **436**. The pressure observer includes a pressure observer processing circuit **438** which further includes a pressure observer memory **440**. The pressure observer memory **440** includes a pressure observer pump analysis module **442** and a pressure observer gain analysis module **444**. The pressure observer **436** is configured to receive the injector duty cycle d_I, the pump frequency f_P, and the measured pressure P_M, and produce the pressure gain P_G. The pressure observer **436** is also configured to receive an injector pulse I_P from the central controller **402**. The injector pulse I_P is equal to one when the injector (e.g., the injector **128**) is energized and zero when the injector is not energized.

FIG. **5** illustrates the pressure observer memory **440** in greater detail. The pressure observer pump analysis module **442** is configured to receive the pump frequency f_P, the injector duty cycle d_I, and the injector pulse I_P. The pressure observer pump analysis module **442** is configured to produce an estimated pressure P_E. The estimated pressure P_E is an estimated (e.g., calculated, determined, etc.) pressure of reductant at an outlet of the pump **426** and/or at an inlet of the pump **426**. The pressure observer gain analysis module **444** is configured to receive the measured pressure P_M from the pump **426**, receive the estimated pressure P_E from the pressure observer pump analysis module **442**, and produce the pressure gain P_G. The pressure gain P_G is a dimensionless factor that represents a comparison between the measured pressure P_M and the estimated pressure P_E.

After receiving the pump frequency f_P, the pressure observer pump analysis module **442** computes an adjusted pump frequency f_{PA}. The adjusted pump frequency f_{PA} is computed by

$$f_{PA} = \frac{num(f_P)}{f_P - 0.9967} \tag{14}$$

where num(f_P) is the real component (e.g., as opposed to any imaginary component, etc.) of the pump frequency f_P. The adjusted pump frequency f_{PA} is computed to account for variations in the pump frequency f_P.

After receiving the injector pulse I_P, the pressure observer pump analysis module **442** computes an adjusted injector pulse I_{PA}. The adjusted injector pulse I_{PA} is computed by

$$I_{PA} = \frac{num(I_P)}{I_P - 0.9967} \tag{15}$$

where num(I_P) is the real component (e.g., as opposed to any imaginary component, etc.) of the injector pulse I_P. The adjusted injector pulse I_{PA} is computed to account for variations in the injector pulse I_P.

After determining the adjusted pump frequency f_{PA} and the adjusted injector pulse I_{PA}, the pressure observer pump analysis module **442** determines a first estimated pressure factor P_{E1} using a discrete state space model

$$x(n+1)=A*x(n)+B*u(n) \tag{16}$$

$$y(n)=C*x(n)+D*u(n) \tag{17}$$

where A, B, C, and D are separate matrices that are determined by a matrix tuning process implemented by the PID controller **406**. To implement the matrix tuning process, the PID controller **406** sets the pump frequency f_P to a constant value, such as 25 Hz or 30 Hz, and sets the injector duty cycle d_I to a constant value, such as 90%. The PID controller **406** then gradually increases (e.g., steps, etc.) the pump frequency f_P and records (e.g., logs, etc.) the measured pressure P_M. After the PID controller **406** records these measured pressures P_M, the PID controller **406** may generate a preliminary 4th order system that fits (e.g., matches, corresponds with, etc.) the recorded measured pressures P_M. The PID controller **406** may generate the preliminary 4th order system in canonical form. After generating the preliminary 4th order system, the PID controller **406** utilizes the preliminary 4th order system in a processing and equipment monitoring (PEM) function to determine a refined system that more accurately fits the data than the preliminary 4th order system. The PID controller **406** then utilizes this refined system to determine A, B, C, and D. In an example embodiment

$$A = \begin{bmatrix} 0.9703 & -0.0243 & -0.6677 \\ -0.0671 & 0.7431 & -1.997 \\ 0.04576 & 0.02095 & -0.646 \end{bmatrix} \tag{18}$$

$$B = \begin{bmatrix} -0.009421 & -0.02121 \\ -0.03859 & -0.08485 \\ -0.0228 & -0.06218 \end{bmatrix} \tag{19}$$

$$C = [\,7.312 \quad -3.155 \quad 0.5125\,] \tag{20}$$

$$D = [\,0 \quad 0\,] \tag{21}$$

where

$$A = \begin{bmatrix} (x(1), x(1)) & (x(1), x(2)) & (x(1), x(3)) \\ (x(2), x(1)) & (x(2), x(2)) & (x(2), x(3)) \\ (x(3), x(1)) & (x(3), x(2)) & (x(3), x(3)) \end{bmatrix} \tag{22}$$

-continued

$$B = \begin{bmatrix} (x(1), u(1)) & (x(1), u(2)) \\ (x(2), u(1)) & (x(2), u(2)) \\ (x(3), u(1)) & (x(3), u(2)) \end{bmatrix} \tag{23}$$

$$C = [\,(y(1), x(1)) \quad (y(1), x(2)) \quad (y(1), x(3))\,] \tag{24}$$

$$D = [\,(y(1), u(1)) \quad (y(1), u(2))\,] \tag{25}$$

The pressure observer pump analysis module **442** also determines a second estimated pressure factor P_{E2} using

$$P_{E2}=K_1+K_2f_P+K_3d_I+K_4|f_P|^2+K_5|d_I|^2 \tag{26}$$

where K_1, K_2, K_3, K_4, and K_5 are constants that are determined by a constant tuning process implemented by the PID controller **406**. To implement the constant tuning process, the PID controller **406** initially sets all of K_1, K_2, K_3, K_4, and K_5 to 0 and implements a test (e.g., design of experiment (DOE, etc.) which sets the pump frequency f_P and injector duty cycle d_I to various values and determines errors between measured pressures P_M and pressures determined by a discrete state space model. After the errors have been determined, a nonlinear regression model of the pump frequencies f_P, injector duty cycles d_I, and the errors is fit to determine the constants K_1, K_2, K_3, K_4, and K_5. In an example embodiment

$$\begin{bmatrix} K_1 \\ K_2 \\ K_3 \\ K_4 \\ K_5 \end{bmatrix} = \begin{bmatrix} -0.5132 \\ 0.026886 \\ -0.022815 \\ -0.010032 \\ 0.000057892 \end{bmatrix} \tag{27}$$

although other values for the constants the constants K_1, K_2, K_3, K_4, and K_5 are possible.

After receiving the second estimated pressure factor P_{E2}, the pressure observer gain analysis module **444** computes an adjusted second estimated pressure factor P_{AE2}. The adjusted second estimated pressure factor P_{AE2} is computed by

$$P_{AE2} = \frac{num(P_{E2})}{P_{E2} - 0.9967} \tag{28}$$

where num(P_{E2}) is the real component (e.g., as opposed to any imaginary component, etc.) of the second estimated pressure factor P_{E2}. The adjusted second estimated pressure factor P_{AE2} is computed to account for variations in the second estimated pressure factor P_{E2}.

Once the first estimated pressure factor P_{E1} and the adjusted second estimated pressure factor P_{AE2} have been determined, the pressure gain P_G is determined by

$$P_G=P_{E1}+P_{AE2} \tag{29}$$

Once the pressure gain P_G has been computed by the pressure observer gain analysis module **444**, the pressure gain P_G is provided to the pressure controller **418**, and the process of determining the compensated flow rate F_C beings again. This operation may be run in a continuous loop such that the pump **426** continues to operate desirably. In this way, the dosing module control system **4200** may optimize operation of the pump **426** according to dimensions of a specific injector associated with the dosing module control system **400**. Additionally, the dosing module control system **400** may be utilized to perform on-board or remote diagnostics. For example, the doser compensation system **404** may communicate with an external system (e.g., a laptop, a computer, a mobile phone, etc.) and transmit, for example, the measured pressure P_M, the pressure gain P_G, the injector duty cycle d_I, the pump frequency f_P, and the pressure error E_P to the external system.

The central controller **402**, the injector controller processing circuit **410**, the pressure controller processing circuit **420**, the pump processing circuit **428**, and/or the pressure observer processing circuit **438** may include a microprocessor, an ASIC, a FPGA, etc., or combinations thereof. The central controller **402** may include memory, which may include, but is not limited to, electronic, optical, magnetic, or any other storage or transmission device capable of providing a processor, ASIC, FPGA, etc. with program instructions. This memory, as well as the injector controller memory **412**, the pressure controller memory **422**, the pump memory **432**, and the pressure observer memory **440**, may include a memory chip, EEPROM, EPROM, flash memory, or any other suitable memory from which the associated controller can read instructions. The instructions may include code from any suitable programming language.

The doser compensation system **404** may be located separate from the central controller **402**. For example, the central controller **402** may be located proximate a front end of a vehicle (e.g., in an engine bay, in a cab, etc.) and the doser compensation system **404** may be located proximate a rear end of a vehicle (e.g., in a cargo bay, in a frame compartment, etc.).

The pressure controller **418** is configured to provide the pump frequency f_P to the injector controller **408**. Additionally, the injector controller **408** is configured to receive the measured pressure P_M and compare the target pressure P_T and the measured pressure P_M to determine a pressure error E_P. The pressure controller **418** is also configured to provide the pressure error E_P to the injector controller **408**.

The PID controller **406** is configured to switch between the first state, where the compensated flow rate F_C is equal to the target flow rate F_T, and the second state, where the compensated flow rate F_C is a function of the target flow rate F_T and an average pressure gain P_{GAvg}, which is a function of a pressure gain P_G. In an example embodiment, the PID controller **406** is configured to operate in the first state when an internal combustion engine associated with the dosing module control system **400** is not powered and when the internal combustion engine is operating at conditions other than steady-state (e.g., warm up, cool down, etc.). In this embodiment, the PID controller **406** is configured to operate in the second state when the internal combustion engine is operating at steady-state and has been operating at steady state for an amount of time t greater than a target amount of time t_{Target} (e.g., 20 seconds, 20 minutes, etc.). In this way, the target amount of time t_{Target} functions like a threshold. In an example embodiment, the target amount of time t_{Target} is 20 seconds.

The PID controller **406** may determine if the internal combustion engine is operating at steady-state by comparing a parameter to maximum and minimum values for that parameter, the maximum and minimum values defining a range of the parameter associated with operation of the internal combustion engine at steady state. In various embodiments, these parameters are the injector duty cycle d_I, the pump frequency f_P, and the pressure error E_P. Accordingly, the PID controller **406** may utilize any combination of the comparisons

$$d_{IMin}<d_I<d_{IMax} \tag{30}$$

$$f_{PMin}<f_P<f_{PMax} \tag{31}$$

$$E_{PMin}<E_P<E_{PMax} \tag{32}$$

to determine if the internal combustion engine is operating at steady state. Specifically, the PID controller **406** may determine that the internal combustion engine is operating at steady state if: the injector duty cycle d_I is greater than a minimum injector duty cycle d_{IMin} and less than a maximum injector duty cycle d_{IMax}; the pump frequency f_P is greater than a minimum pump frequency f_{PMin} and less than a maximum pump frequency f_{PMax}; and/or the pressure error E_P is greater than a minimum pressure error E_{PMin} and less than a maximum pressure error E_{PMax}. The PID controller **406** may perform these comparisons continuously (e.g., at each time step, etc.). For example, the PID controller **406** may perform these comparisons continuously while the internal combustion engine is operational and not perform these comparisons while the internal combustion engine is not operational.

As previously mentioned, the compensated flow rate F_C is a function of the average pressure gain P_{GAvg}. The average pressure gain P_{GAvg} is determined continuously once the PID controller **406** has been in the second state for an amount of time t greater than the target amount of time t_{Target}. For example, so long as the injector duty cycle d_I is greater than the minimum injector duty cycle d_{IMin} and less than the maximum injector duty cycle d_{IMax}, and the amount of time t is greater than the target amount of time t_{Target}, the average pressure gain P_{GAvg} may be determined. Once the PID controller **406** switches from the second state back to the first state, the amount of time t is reset back to 0 but will restart (e.g., count from 0 upwards) once the PID controller **406** is in the second state again. In this way, the amount of time t may be thought of as recording an amount of time that the PID controller **406** has been in the second state at the present instance of the PID controller **406** being in the second state (e.g., rather than a total amount of time that the PID controller **406** has been in the second state without regard to whether or not the PID controller **406** has been in the first state since initially entering the second state, etc.).

The amount of time t is a discrete output from a discrete time integration, using a unit delay, of an actual amount of time t_{Actual} that the PID controller **406** has been in the second state. Like the amount of time t, the actual amount of time t_{Actual} is also reset back to 0 when the PID controller **406** enters the first state, but will restart once the PID controller **406** enters the second state. The unit delay is equal to the amount of time t at one time step prior (e.g., n−1, etc.) to the time step (e.g., n, etc.) at which the actual amount of time t_{Actual} is determined, where the amount of time t is greater than the target amount of time t_{Target}.

To determine the average pressure gain P_{GAvg}, the pressure gain P_G is first passed through a discrete time integration using the unit delay. The pressure gain P_G is then divided by the amount of time t, without regard as to the target amount of time t_{Target}, to determine the average pressure gain P_{GAvg}. However, the PID controller **406** only utilizes the average pressure gain P_{GAvg} in computing the compensated flow rate F_C if the amount of time t is greater than the target amount of time t_{Target}.

V. Construction of Example Embodiments

While the dosing module control system **200** is shown and described as including the flow observer **236**, it is understood that the dosing module control system **200** may additionally or alternative include the pressure observer **436** and the injector controller **408**. In these embodiments, the dosing module control system **200** may determine the compensated flow F_C according to the average pressure gain P_{GAvg} and/or the average flow rate gain F_{GAvg}.

While the dosing module control system **400** is shown and described as including the pressure observer **436**, it is understood that the dosing module control system **400** may additionally or alternative include the flow controller **208**, the driver **225**, and the flow observer **236**. In these embodiments, the dosing module control system **400** may determine the compensated flow F_C according to the average pressure gain P_{GAvg} and/or the average flow rate gain F_{GAvg}.

While this specification contains many specific implementation details, these should not be construed as limitations on the scope of what may be claimed but rather as descriptions of features specific to particular implementations. Certain features described in this specification in the context of separate implementations can also be implemented in combination in a single implementation. Conversely, various features described in the context of a single implementation can also be implemented in multiple implementations separately or in any suitable subcombination. Moreover, although features may be described as acting in certain combinations and even initially claimed as such, one or more features from a claimed combination can, in some cases, be excised from the combination, and the claimed combination may be directed to a subcombination or variation of a subcombination.

As utilized herein, the terms "substantially," generally," and similar terms are intended to have a broad meaning in harmony with the common and accepted usage by those of ordinary skill in the art to which the subject matter of this disclosure pertains. It should be understood by those of skill in the art who review this disclosure that these terms are intended to allow a description of certain features described and claimed without restricting the scope of these features to the precise numerical ranges provided. Accordingly, these terms should be interpreted as indicating that insubstantial or inconsequential modifications or alterations of the subject matter described and claimed are considered to be within the scope of the invention as recited in the appended claims.

The terms "coupled" and the like, as used herein, mean the joining of two components directly or indirectly to one another. Such joining may be stationary (e.g., permanent) or moveable (e.g., removable or releasable). Such joining may be achieved with the two components or the two components and any additional intermediate components being integrally formed as a single unitary body with one another, with the two components, or with the two components and any additional intermediate components being attached to one another.

The terms "fluidly coupled to," "fluidly configured to communicate with," and the like, as used herein, mean the two components or objects have a pathway formed between the two components or objects in which a fluid, such as air, liquid reductant, gaseous reductant, aqueous reductant, gaseous ammonia, etc., may flow, either with or without intervening components or objects. Examples of fluid couplings or configurations for enabling fluid communication may include piping, channels, or any other suitable components for enabling the flow of a fluid from one component or object to another.

It is important to note that the construction and arrangement of the system shown in the various example implementations is illustrative only and not restrictive in character. All changes and modifications that come within the spirit and/or scope of the described implementations are desired to be protected. It should be understood that some features may not be necessary, and implementations lacking the various features may be contemplated as within the scope of the application, the scope being defined by the claims that follow. When the language "a portion" is used, the item can include a portion and/or the entire item unless specifically stated to the contrary.

What is claimed is:

1. A dosing module control system comprising:

a central controller configured to obtain a target flow rate and a target pressure;

a flow observer configured to determine a flow rate gain;

a switching doser controller configured to communicate with the central controller and the flow observer and configured to:

receive the target flow rate and the target pressure from the central controller,

receive the flow rate gain from the flow observer,

determine a compensated flow rate based on the target flow rate, the target pressure, and the flow rate gain, and

determine at least one of an injector duty cycle associated with the determined compensated flow rate, or a pump frequency associated with the determined compensated flow rate; and

a pump configured to communicate with the switching doser controller, the pump configured to receive the at least one of the injector duty cycle or the pump frequency from the switching doser controller and to operate based on the at least one of the determined injector duty cycle or the determined pump frequency to provide reductant at the compensated flow rate.

2. The dosing module control system of claim **1**, wherein:

the pump is configured to communicate with the flow observer;

the pump comprises a pressure sensor configured to determine a measured pressure associated with the reductant in the pump; and

the flow observer is configured to receive the measured pressure from the pump.

3. The dosing module control system of claim **2**, wherein:

the flow observer is configured to receive the at least one of the injector duty cycle or the pump frequency from the switching doser controller; and

the flow observer is configured to determine the flow rate gain based on the at least one of the injector duty cycle or the pump frequency from the switching doser controller and the measured pressure.

4. The dosing module control system of claim **2**, wherein:

the switching doser controller is configured to receive the measured pressure from the pump; and

the switching doser controller is configured to determine a pressure error by comparing the measured pressure to the target pressure.

5. The dosing module control system of claim **4**, wherein:

the switching doser controller is operable between a first state and a second state;

the switching doser controller is configured to set the compensated flow rate equal to the target flow rate in the first state; and

the switching doser controller is configured to cause the compensated flow rate to be other than the target flow rate in the second state.

6. The dosing module control system of claim **5**, wherein:

the switching doser controller is configured to compare the pressure error to a minimum pressure error and a maximum pressure error;

the switching doser controller is caused to be in the first state in response to the pressure error being less than or equal to the minimum pressure error or greater than or equal to the maximum pressure error; and

the switching doser controller is caused to be in the second state in response to the pressure error being greater than the minimum pressure error and less than the maximum pressure error.

7. The dosing module control system of claim **1**, wherein the at least one of the injector duty cycle or the pump frequency is both the injector duty cycle and the pump frequency.

8. The dosing module control system of claim **1**, wherein:

the switching doser controller is operable between a first state and a second state;

the switching doser controller is configured to set the compensated flow rate equal to the target flow rate in the first state; and

the switching doser controller is configured to cause the compensated flow rate to be other than the target flow rate in the second state.

9. The dosing module control system of claim **8**, wherein:

the at least one of the injector duty cycle or the pump frequency is at least the injector duty cycle;

the switching doser controller is configured to compare the injector duty cycle to a minimum injector duty cycle and a maximum injector duty cycle;

the switching doser controller is caused to be in the first state in response to the injector duty cycle being less than or equal to the minimum injector duty cycle or greater than or equal to the maximum injector duty cycle; and

the switching doser controller is caused to be in the second state in response to the injector duty cycle being greater than the minimum injector duty cycle and less than the maximum injector duty cycle.

10. The dosing module control system of claim **8**, wherein:

the at least one of the injector duty cycle or the pump frequency is at least the pump frequency;

the switching doser controller is configured to compare the pump frequency to a minimum pump frequency and a maximum pump frequency;

the switching doser controller is caused to be in the first state in response to the pump frequency being less than or equal to the minimum pump frequency or greater than or equal to the maximum pump frequency; and

the switching doser controller is caused to be in the second state in response to the pump frequency being greater than the minimum pump frequency and less than the maximum pump frequency.

11. A dosing module control system comprising:

a central controller configured to obtain a target flow rate and a target pressure;

a pressure observer configured to determine a pressure gain;

a proportional-integral-derivative (PID) controller configured to communicate with the central controller and the pressure observer and configured to:

  receive the target flow rate and the target pressure from the central controller,

  receive the pressure gain from the pressure observer,

  determine a compensated flow rate based on the target flow rate, the target pressure, and the pressure gain, and

  determine at least one of an injector duty cycle associated with the compensated flow rate, or a pump frequency associated with the compensated flow rate; and

a pump configured to communicate with the PID controller, the pump configured to receive the at least one of the injector duty cycle or the pump frequency from the PID controller and to operate based on the at least one of the injector duty cycle or the pump frequency to provide reductant at the compensated flow rate.

12. The dosing module control system of claim **11**, wherein:

the pump is configured to communicate with the pressure observer;

the pump comprises a pressure sensor configured to determine a measured pressure associated with the reductant in the pump; and

the pressure observer is configured to receive the measured pressure from the pump.

13. The dosing module control system of claim **12**, wherein:

the pressure observer is configured to receive the at least one of the injector duty cycle or the pump frequency from the PID controller; and

the pressure observer is configured to determine the pressure gain based on the at least one of the injector duty cycle or the pump frequency from the PID controller and the measured pressure.

14. The dosing module control system of claim **12**, wherein:

the PID controller is configured to receive the measured pressure from the pump; and

the PID controller is configured to determine a pressure error by comparing the measured pressure to the target pressure.

15. The dosing module control system of claim **14**, wherein:

the PID controller is operable between a first state and a second state;

the PID controller is configured to set the compensated flow rate equal to the target flow rate in the first state; and

the PID controller is configured to cause the compensated flow rate to be other than the target flow rate in the second state.

16. The dosing module control system of claim **15**, wherein:

the PID controller is configured to compare the pressure error to a minimum pressure error and a maximum pressure error;

the PID controller is caused to be in the first state in response to the pressure error being less than or equal to the minimum pressure error or greater than or equal to the maximum pressure error; and

the PID controller is caused to be in the second state in response to the pressure error being greater than the minimum pressure error and less than the maximum pressure error.

17. The dosing module control system of claim **11**, wherein the at least one of the injector duty cycle or the pump frequency is both the injector duty cycle and the pump frequency.

18. The dosing module control system of claim **11**, wherein:

the PID controller is operable between a first state and a second state;

the PID controller is configured to set the compensated flow rate equal to the target flow rate in the first state; and

the PID controller is configured to cause the compensated flow rate to be other than the target flow rate in the second state.

19. The dosing module control system of claim **18**, wherein:

the at least one of the injector duty cycle or the pump frequency is at least the injector duty cycle;

the PID controller is configured to compare the injector duty cycle to a minimum injector duty cycle and a maximum injector duty cycle;

the PID controller is caused to be in the first state in response to the injector duty cycle being less than or equal to the minimum injector duty cycle or greater than or equal to the maximum injector duty cycle; and

the PID controller is caused to be in the second state in response to the injector duty cycle being greater than the minimum injector duty cycle and less than the maximum injector duty cycle.

20. The dosing module control system of claim **18**, wherein:

the at least one of the injector duty cycle or the pump frequency is at least the pump frequency;

the PID controller is configured to compare the pump frequency to a minimum pump frequency and a maximum pump frequency;

the PID controller is caused to be in the first state in response to the pump frequency being less than or equal to the minimum pump frequency or greater than or equal to the maximum pump frequency; and

the PID controller is caused to be in the second state in response to the pump frequency being greater than the minimum pump frequency and less than the maximum pump frequency.

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